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ULTRASONIC INSPECTION OF FILAMENT WOUND GRAPHITE EPOXY CYLINDERS

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MATERIALS TESTING AND EVALUATION BRANCH

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ABSTRACT

A nondestructive inspection procedure utilizing ultrasonic C-scan imaging was developed to test cylindrical filament wound graphite epoxy rocket motor cases. These cylinders are part of a joint U.S. Army, Navy, NASA, and Air force (JANNAF) research round robin to evaluate destructive testing techniques for this type of composite. The rocket motor cases are made from T650/42 graphite fibers (Amoco) in a Lincoln Resin Formulation (LRF) and have six layers (twelve plies).

The ultrasonic method used to evaluate the rocket motor cases was immersion, pulse-echo defect C-scans. Difficulties and solutions of using this method to evaluate the rocket motor cases will be discussed.

The received ultrasonic signals were evaluated for reflections from discontinuities within the material by means of an electronic gate set between the front and back surface reflections. The signals were then imaged in color on a computer according to the amplitude of the reflections. The resultant color C-scans were evaluated to separate the good from the bad. In some rocket motor cases there appeared to be large delaminations and inclusions. There were also some that showed few or no defect indications. Ultrasonic attenuation and time-of-flight (velocity) scans were performed to evaluate their quality. Contact time-of-flight measurements were also taken on a number of cylinders to verify immersion results. Comparisons will be made with transverse compression, transverse tension, and in-plane shear destructive test results. These comparisons will verify the usefulness of electronically gated ultrasonic immersion, pulse echo, defect C-scans on filament wound cylinders.

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INTRODUCTION

This paper will address a procedure designed to inspect thin, filament wound, graphite epoxy cylinders. The objectives of this project were to develop a procedure to ultrasonically evaluate filament wound graphite epoxy cylinders and to determine the feasibility of electronically grated C-scans for thin composites. The ultrasonic NDE method employed was immersion, pulse-echo, defect C-scans.[1]

C-scans are a plan view of the specimen. In the case of cylindrical specimens inspected using a turntable, C-scans represent the plan view that would be obtained if the cylinder wall were cut and the cylinder spread to make a rectangle. C-scans are produced by sending and receiving an ultrasonic pulse through the cylinder wall and recording the decivolt amplitude of reflections that occur within an electronic gate that is set up between the front and back surface reflections. These amplitudes are then imaged through a computer on a color display. Similar work utilizing feature mapping developed by Rose[2] was done to examine and identify anomalies in graphite epoxy panels.[3]

Recent developments in filament winding and fiber placement technology have improved the process of manufacturing composite materials.[4] This is important because more control over the manufacturing process can be achieved to reduce void content in the manufactured parts. Variations in material properties of composites can affect the detection of defects by ultrasound. High attenuation of sound due to scattering by the fibers, and absorption in the epoxy resin are two examples.[5] Transducer frequency selection must be carefully made so that the ultrasonic pulse will penetrate through the material while the wavelength is short enough to pick up any small defects present.

The composite cylinders inspected were made from T650/42 graphite fibers (Amoco) in a Lincoln Resin Formulation (LRF).[6] They have six layers (twelve plies), 4 inches (10.16 cm) inside diameter, 5.5 inches (13.97 cm) long, and 0.075 inch (0.191 cm) wall thickness as shown in Figure 1. The wind angle was 90° (pi/2 rads) and the winding tension was 5 lbs. In total, 360 cylinders, cut from 60 larger cylinders, were inspected. They are part of a round robin research effort to determine the effectiveness of different destructive tests. The destructive tests were performed to determine transverse compression, transverse tension, and in-plane shear strength and modulus. Ultrasonic NDE was performed on all of the cylinders prior to destructive testing to evaluate the usefulness of the electronically gated C-scans.

INSPECTION PROBLEMS

The ultrasonic inspection of composite cylinders can pose many problems. Inherently, high strength fibers such as graphite are difficult to fabricate with a high degree of uniformity. Discontinuities that can be found in filament wound composite cylinders include resin

1. *Nondestructive Evaluation and Quality Control.* Metals Handbook, 9th ed., v. 17, ASM International, Metals Park, OH, 1989, p. 241-243.
2. ROSE, J. L. *Elements of a Feature-based Ultrasonic Inspection System.* Materials Evaluation, v. 42, no. 2, February 1984, p. 210-226.
3. NETLEROTH, J. B., ROSE, J. L., BASHYAM, M., and SUBRAMANIAN, K. *Physically Based Ultrasonic Feature Mapping for Anomaly Classification in Composite Materials.* Materials Evaluation, v. 43, no. 5, April 1985, p. 541-546.
4. STOVER, D. *Filament Winding and Fiber Placement: Stretching the Bounds of an Automated Process.* Advanced Composites, v. 5, November-December 1990, p. 20-35.
5. BAR-COHEN, U. *NDE of Fiber-Reinforced Composite Materials - A Review.* Materials Evaluation, v. 44, no. 4, March 1986, p. 447.
6. McGEE, J., SPENCER, B., SHY, D. *Feasibility Study on the Design of Reinforced Plastic Components for the LVTP (7) Vehicle Shafts.* U.S. Army Materials Technology Laboratory, AMMRC TR 84-27, December 1984, p. 31.

pockets, localized variations of wall thickness, cracks and delaminations, and variations of resin thickness.[7] These along with the high attenuation of fiber composites caused by small reflectors can make ultrasonic evaluation difficult.

Transducer selection was difficult due to the thinness of the cylinder. High frequency transducers are generally used on thin materials because of their shorter wavelengths. They have a high degree of sensitivity and resolution. However, more scattering of the sound may occur which can reduce penetration of sound through the material than if using a lower frequency transducer. Therefore, a transducer frequency must be chosen that is low enough to completely penetrate the cylinder wall but high enough to have the necessary bandwidth to limit the ringing effect of the transducer and provide good sensitivity and resolution since the cylinder wall is so thin. It is important to limit the ringing of the transducer because this causes an area near the surface of the wall in which no discontinuities can be resolved.

Penetration is a problem in this composite because the inhomogeneous nature of composites can cause diffractions, reflections, and refractions. There will be much wave scattering, thus increasing signal attenuation. In practice, the best way to choose the transducer is by the trial and error method. The highest frequency that can penetrate the material and return a signal from the back wall should be chosen. Too high a frequency, however, will create more noise and yield a low signal-to-noise ratio (SNR). Numerous transducers from 5 MHz to 25 MHz with 0.25 inch and 0.5 inch diameters, focused and unfocused, were evaluated for optimal signal reflections from the cylinders. In practice, a 15 MHz, 0.25 inch diameter, unfocused transducer yielded the best result. Since there were no official acceptance/rejection criteria, and this was a comparative evaluation, there was freedom in the selection of the transducer.

The outside surface condition of the cylinder made the ultrasonic inspection of this material difficult. It had a rough surface because of the inherent effect of the winding process. The inside surface, however, was smooth because the fibers and epoxy contoured to the mandrel during the winding process.

Perhaps the biggest difficulty in inspecting these cylinders was keeping a consistent distance and angle from the transducer to the cylinder. If the cylinder on the turntable is off center or it is not normal (90°) to the transducer, the signals will have inconsistent results as the cylinder rotates and the transducer moves. Even if the transducer is only a couple of degrees away from the normal angle of incidence (the angle where the ultrasonic signal and the surface of the cylinder meet), then the amplitude of any reflections could be significantly decreased. Another problem when the incidence angle is not normal to the surface of the cylinder is that the distance between the transducer and the point of contact of the sound wave to the surface of the cylinder wall will vary as the transducer moves up the rotating cylinder. The transducer to wall distance will also vary if the cylinder is not exactly centered on the turntable.

Another decision that had to be made was the choice of which technique to use; velocity, defect, or attenuation scans. Velocity scans are produced by monitoring and imaging the flight time of the ultrasonic signal through the cylinder wall. Defect scans are produced by monitoring and imaging the amplitude changes caused by discontinuities and defects within a gated region between the front and back surfaces. Attenuation scans are produced by monitoring and imaging the amplitude of the back reflection of the sound wave.

7. *Ultrasonic Testing*, Nondestructive Testing Handbook, ASNT, v. 7, 2nd ed., Columbus, OH, 1991, p. 246-247.

INSPECTION SOLUTIONS

Standards

Reference standards were required to establish the ultrasonic equipment sensitivity and to verify that the instruments and transducer were working properly. Reference standards had to be specially fabricated with artificial defects for this project. The artificial defects were implanted during the winding process. Initially, the cylinders were fabricated with a 0.040 inch (0.102 cm) wall thickness. A set of reference standards was fabricated with the same wall thickness. C-scans could not be performed on these cylinders because the reflection from the inside back of the wall was occurring in time before the reflection from the front surface stopped ringing. Attempts to use higher frequency transducers with a wider bandwidth were unsuccessful because of poor sound penetration. Another contributor to the poor C-scan quality was the problem of exactly centering the cylinder. Very thin cylinders are especially sensitive to incidence angle variations.

After a few iterations of wall thicknesses, standards were finally fabricated with a wall thickness of 0.70 inch (0.178 cm). Artificial defects made from aluminum foil and Kapton film were implanted in the cylinders during fabrication. The thickness of the aluminum foil was approximately 0.001 inch (0.003 cm) and the thickness of the Kapton film was approximately 0.002 inch (0.005 cm). There were seven aluminum foil defects and five Kapton film defects. The defects were circular with diameters of 0.1395 inch (0.354 cm), 0.1820 inch (0.462 cm), 0.2330 inch (0.592 cm), 0.2820 inch (0.716 cm), and 0.3215 inch (0.817 cm), placed after the sixth ply. To evaluate how much of the wall thickness was being evaluated, the two additional aluminum foil defects of 0.2820 inch (0.716 cm) were placed at the third and ninth plies within the wall. A small notch was also cut in the cylinder to test signal loss for velocity scan imaging purposes. The final dimensions for the calibration cylinder were 5.5 inches (13.97 cm) long, 4 inches (10.16 cm) inside diameter, and approximately 0.070 inch (0.178 cm) wall thickness. The wind angle was 90^{0} (pi/2 rads) and the winding tension was 5 lbs. The reference standard, however, was not made at the same facility as the actual test cylinders. It was made as close as possible to the known specifications. Accordingly, several equipment corrections were made when scanning the test specimens. These will be discussed in the experimental procedure.

Fixtures

An important contribution to the quality of these scans lies in the fabrication of specialty fixtures. As previously shown, small variations in positioning can cause very detrimental affects on the resultant C-scans. The following is a brief description of each fixture and its purpose.

The first fixture attached to the turntable was a leveling fixture as shown in Figure 2. It was attached to the center of the turntable and was made up of the base and the top. The base was concave and the top was convex. When fit together, the fixture could be adjusted by any of three set screws to ensure that the cylinder was perpendicular to the direction of the ultrasonic pulse.

The second fixture attached to the top of the leveling fixture. This was a concave cone fixture, as shown in Figure 3. This fixture held the cylinder in the exact center of the turntable axis of rotation and also enabled the transducer to fully scan the bottom of the cylinder. A V-block and level were used with this fixture to assist in alignment of the cylinder. A convex cone fixture was also made in case scanning from the outside of the cylinders was necessary.

Ultrasonic and Computer Hardware

The ultrasonic equipment utilized to perform defect and attenuation C-scan imaging was a digital AI/Sperry QC-2000 reflectoscope pulser/receiver, a Panametrics 15 MHz, 0.25 inch diameter, unfocused, immersion transducer, and a Testech MIS-100 ultrasonic scanner, as shown in Figure 4. The equipment was controlled by an IBM PC-AT through the GPIB Bus and the parallel port. The C-scan data was sent through an A/D converter and imaged on an IBM PGA graphics board with a resolution of 640 x 480. Hard copy output was provided by a Mitsubishi Thermal Transfer Printer. The software that controlled the system and provided imaging was written at the U.S. Army Material Technology Laboratory (MTL), Nondestructive Evaluation (NDE) Group. A diagram of the system is shown in Figure 5. Velocity C-scan imaging utilized the same equipment except the pulser/receiver and A/D converter. Instead, a Panametrics 5215-1C ultrasonic gage was used to extract time-of-flight information and a Tektronix oscilloscope was used to monitor reflections.[8]

EXPERIMENTAL PROCEDURE

The experimental procedure was initially created with the standard cylinders that contained artificial defects and adapted for the actual test specimens because of minor dimensional and material differences. The first step in creating the inspection procedure was to find the material's longitudinal time-of-flight and velocity. A contact pulse-echo overlap method was used. An average flight time of 1.7 μsec. was determined by taking a number of readings. The average wall thickness at these points was measured to be 0.0725 inch (0.184 cm). Calculation of the longitudinal velocity in pulse-echo mode is as follows:

$$\text{longitudinal velocity} = \frac{2 \times \text{thickness}}{\text{time}}$$

$$= \frac{2 \times 0.0725}{1.7 \times 10^{-6}} = 85.294 \text{ inches/sec.} \tag{1}$$

The flight time and velocity will serve as a reference when setting up the equipment in the immersion tank.

Sensitivity, the ability to detect small flaws within the cylinder, is also important to determine. The following calculation shows the sensitivity of the procedure using a 15 MHz transducer.

$$\text{Sensitivity} = \frac{1}{2}\lambda$$

$$= \frac{1}{2} \times \frac{85.294}{15 \times 10^{6}} = 0.0000028 \text{ inch } (0.0000072 \text{ cm}) \tag{2}$$

where:

λ = wavelength

8. GRUBER, J. J., SMITH, J. M., and BROCKELMAN, R. H. *Ultrasonic Velocity C-Scans for Ceramic and Composite Material Characterization.* Materials Evaluation, v. 46, no. 1, January 1988, p. 90-96.

The discrete pixel resolution of the resultant C-scans is 200 x 200 by software design. The vertical resolution, which in this case is the scanning index, is calculated:

$$\frac{\text{Height}}{200} \tag{3}$$

$$= \frac{5.5 \text{ inches}}{200} = 0.0275 \text{ inch } (0.070\text{cm})$$

The circumferential resolution is calculated by:

$$\frac{C}{200} = \frac{2 \times \pi \times r}{200} \tag{4}$$

$$= \frac{2 \times \pi \times 2 \text{ inches}}{200} = 0.0628 \text{ inch } (0.160\text{cm})$$

The next step was to use the fixtures previously described to center the cylinder and make sure that it was level; then the transducer position was optimized manually. These steps are crucial to the quality of the C-scans. Transducer distance was determined by moving the transducer away from the cylinder wall until the second front surface reflection occurred in time after the first back surface reflection.

Scanning from inside the cylinder was chosen because of the affects of the sound entering a concave surface. As illustrated in Figure 6, the concavity of the inside of the cylinder focused the sound path so that less beam spread took place. This meant that more energy was transmitted to a smaller area. Signals that were studied from both the inside and the outside of the cylinder verified that better results were obtained from scanning from the inside. Another contributor to the inside surface yielding better results was that the inside surface was much smoother than the outside surface. This caused less scattering of the ultrasound as it first entered the wall.

The last step before scanning was to obtain the correct settings on the pulser/receiver. The receiver gain was adjusted until the smallest artificial defect from the Kapton Film in the cylinder reached 100 dV amplitude on the A-scan display. Damping was set to a minimum and the gain was increased. The pulser/receiver utilized discrete steps for the damping. A damping value of 50 ohms was chosen such that the signal displayed less ringing but still maintained good amplitude. The formal ultrasonic C-scan procedure is in Appendix A. There were two corrections made to the settings from the calibration standard to the actual test cylinders. The gain had to be slightly decreased and the gate length had to be increased. The reason for this is that the test cylinders were slightly thicker than the standards and were also slightly less attenuative to the sound wave.

After equipment warm-up of about one hour, the calibration standard was used to calibrate the pulser/receiver at the beginning of the day, at four hour intervals, and at the end of the day. If any settings had to be readjusted, all cylinders examined during that interval were reexamined. The tests were verified by alternate personnel rechecking selected and random scans.

Attenuation, velocity, and defect scans were run to determine the quality of each.

Attenuation scans measure the signal loss throughout the cylinder wall by monitoring the amplitude of the back surface reflection of the A-scan. These scans were not very successful because of the large amount of attenuation caused by wave scattering, as shown in Figure 7. The color bar to the right of the attenuation scan represents amplitude changes of the back surface reflection. Colors at the top of the bar represent large back surface reflections. Colors at the bottom of the bar represent smaller reflections from the back surface of the cylinder.

Velocity scans measure the sound velocity through the cylinder wall by triggering a gate at the front surface reflection and stopping the gate at the back reflection. These scans yielded decent results but the small variation in flight time caused by the defects did not allow them to always be clearly visible, as shown in Figure 8. The color bar on the right side of the scan represents the different times of flight that occurred within the cylinder. Numbers at the top of the color bar represent a longer time of flight (slower velocity). Numbers at the bottom of the color bar represent less time that the sound travels through the cylinder (faster velocity).

Defect scans yielded the best results on the artificial defects. Defect scans monitor any reflections that occur within a specified gate set up between the front and back surface reflections of the A-scan. All defects were clearly visible. The amplitude of the reflections of the A-scans were clear. The defects in the third and ninth layer were also clearly visible. The defect in the ninth layer was slightly clearer due to the fact that it was not close to the ringing of the transducer. The gain of the ultrasonic instrument was set to display the smallest Kapton defect (0.1395 inch) (0.354 cm) reflection to an amplitude of 100 dV (40 dB). Figure 9 shows the resultant C-scan of the standard. The color bar on the right side of the defect scan represents amplitude changes of the ultrasonic signal that occur within the gate setup between the front and back surface. Colors at the top of the bar represent greater amplitudes of the signal. Colors at the bottom of the color bar represent small amplitudes.

The electronic gate is the only area under which a discontinuity can be detected. The gate was covering approximately 70% of the total wall thickness. Since we can extend the gate to almost the edge of the back surface, the majority of the area which was not being inspected was located towards the front of the transducer. Because of time restraints, it was not feasible to inspect the cylinders from both the inside and the outside, but this could have been done for a more complete inspection. Each cylinder took approximately 20 minutes to set up, scan, and print.

CONCLUSION

It is important to remember at this time that this was a comparative test and that the results are not to be evaluated with accept/reject criteria. It was found that many scans showed very little defective area. Examples of these are in Appendix B. Other scans showed areas where there were longitudinal defects occurring through the length of the scans. These most likely were areas of delamination. A few of these scans are also shown in Appendix B. Other defects had a shape other than longitudinal to the scan. These defects were most likely caused by inclusions or other discontinuities. The most informative method of evaluating the results of the C-scans was to set an amplitude threshold based on an average or low-amplitude scan that was above the inherent noise level found in all of the cylinders and evaluate the amplitudes above that level. Consider the percentage of the scans above the threshold as indications of the amount of defective area within the specimen. The defective cylinders could then be ranked and compared with the destructive test data. The scans with a large percentage of area above the threshold are the ones most likely to have gross anomalies. These are the cylinders that should be watched closely in the destructive tests. The destructive tests that will be run are transverse compression, transverse tension, and in-plane shear.

RECOMMENDATIONS

Although the results were very encouraging to ultrasonic evaluation of composites, there are some recommendations that would provide for better future results. The biggest limitation to this experiment was the 70% thickness being evaluated. This was due to a combination of transducer characteristics and the material composition and thickness. It is crucial to try different transducers to optimize the A-scan. A broadband transducer should be chosen to limit the ringing of the transducer, but also provide enough penetration. It is important to ensure that the angle of incidence is uniform at 90°. It would also be beneficial to eliminate the electronic gate. This would require digitizing the A-scan signal and using signal processing techniques to extract more information yielding a better percent thickness being evaluated and better resolution and sensitivity. For example, techniques exist to implement a Synthetic Aperture Focusing Technique (SAFT) algorithm or Fourier Transform (FT) SAFT on the digitized A-scan signals before they are imaged. This, however, would be very memory intensive and require much time making this technique inappropriate for many applications.

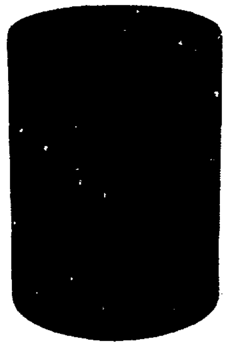


Figure 1. Filament wound graphite epoxy cylinder.

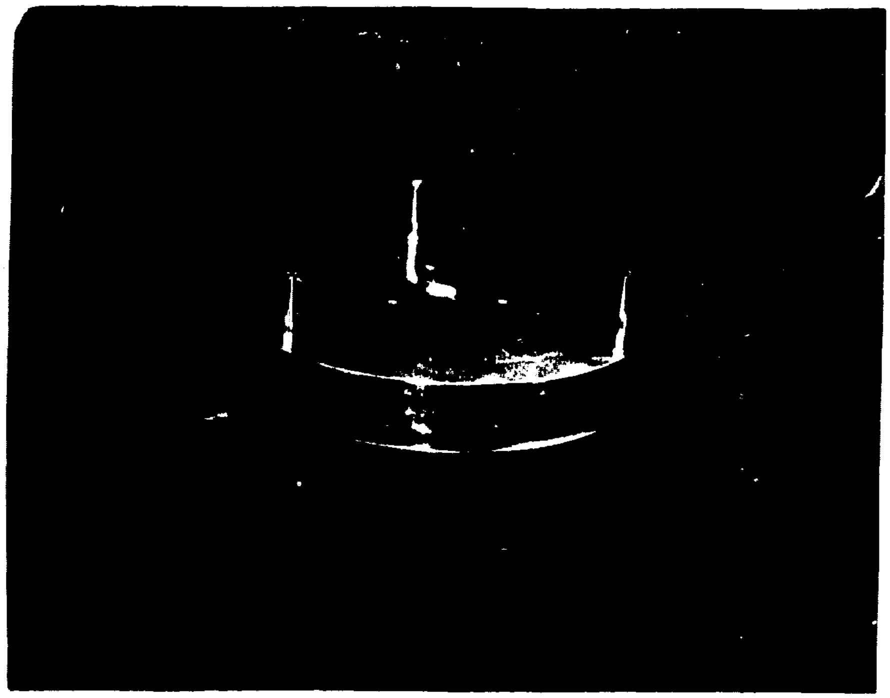


Figure 2. Leveling fixture used on turntable to ensure that the cylinder was perpendicular to the direction of the ultrasonic pulse.

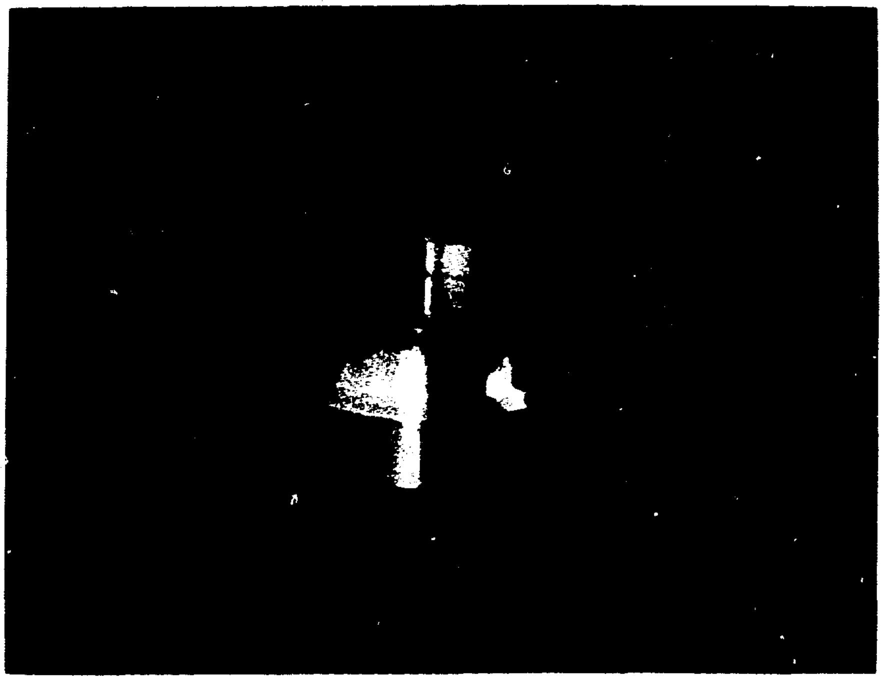


Figure 3. Concave cone fixture. This is attached to the leveling fixture and holds the cylinder in the exact center of the turntable.

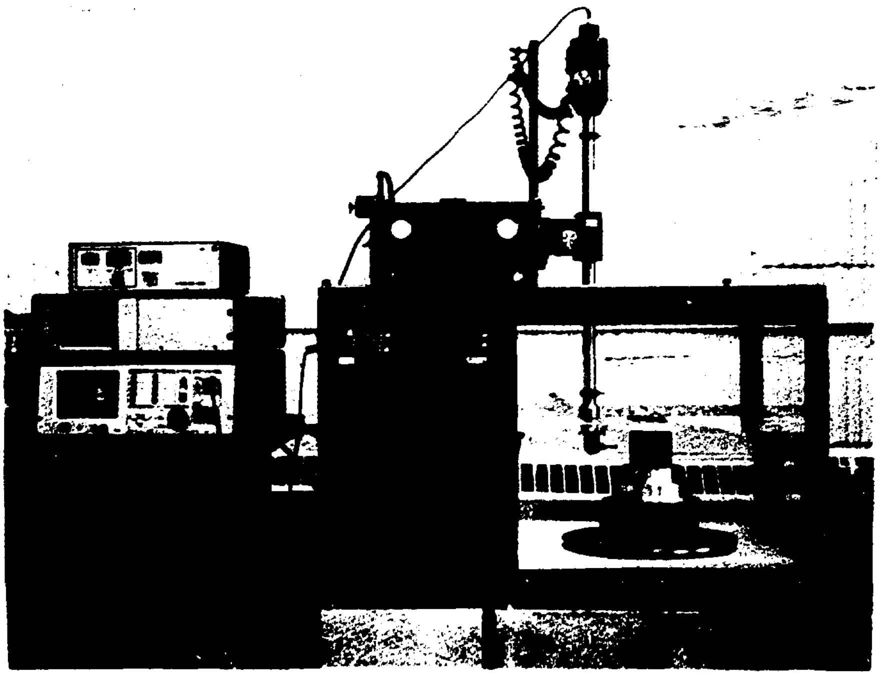


Figure 4. Ultrasonic scanner and pulser/receiver used to inspect filament wound graphite epoxy cylinders.

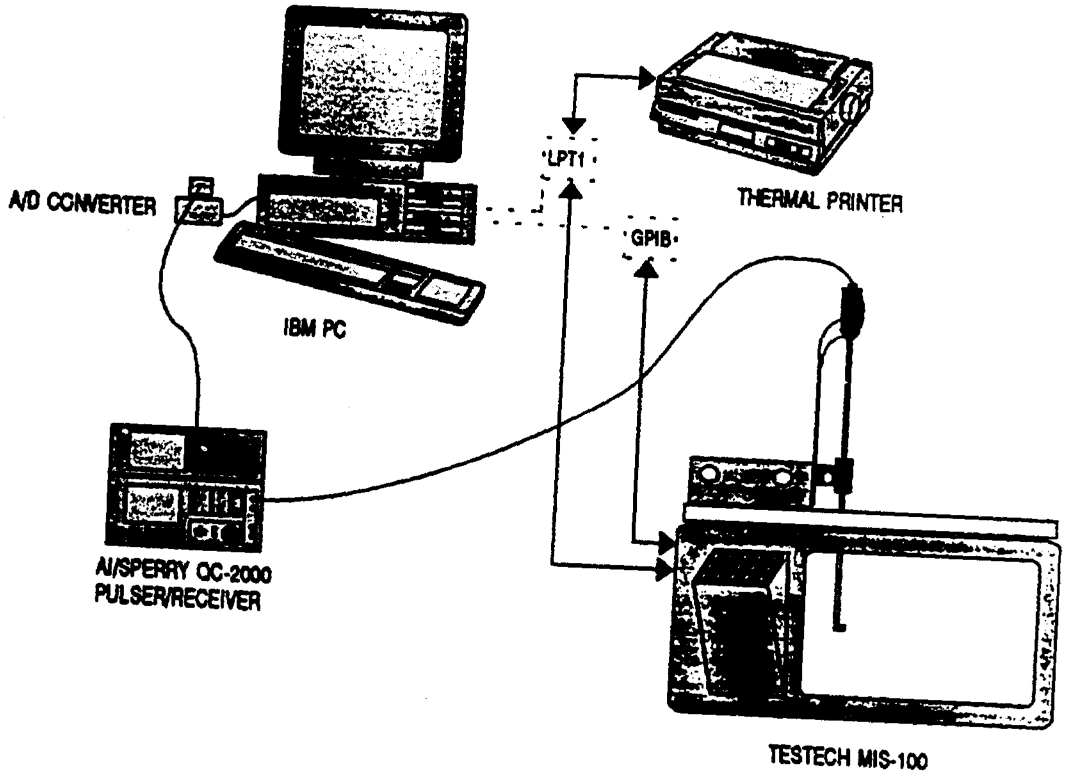


Figure 5. Diagram of ultrasonic defect C-scan inspection system.

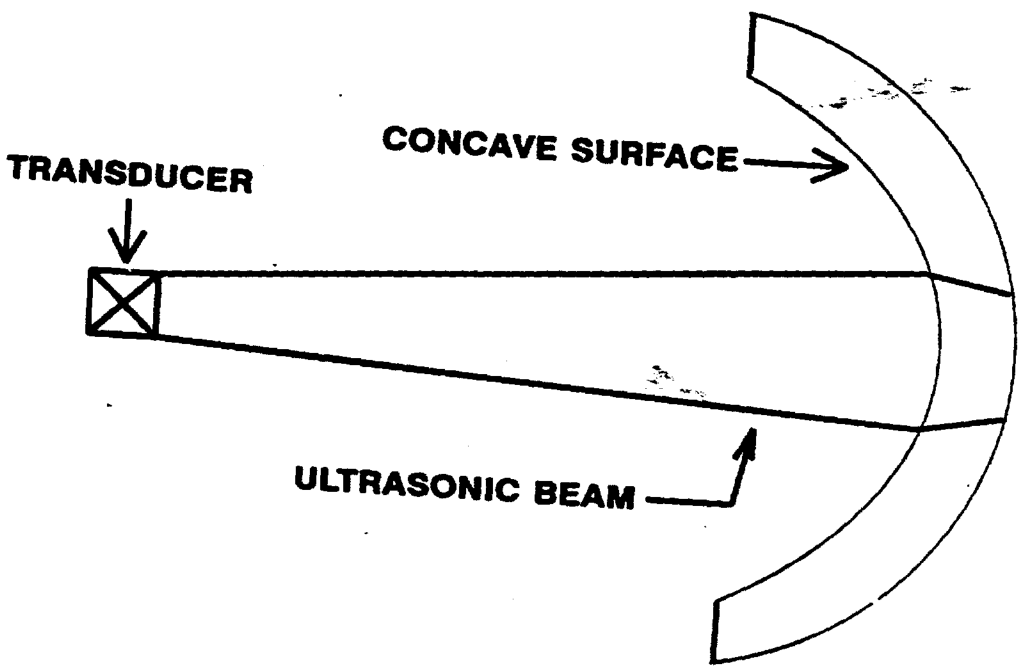


Figure 6. Effect of concave surface on ultrasonic beam.

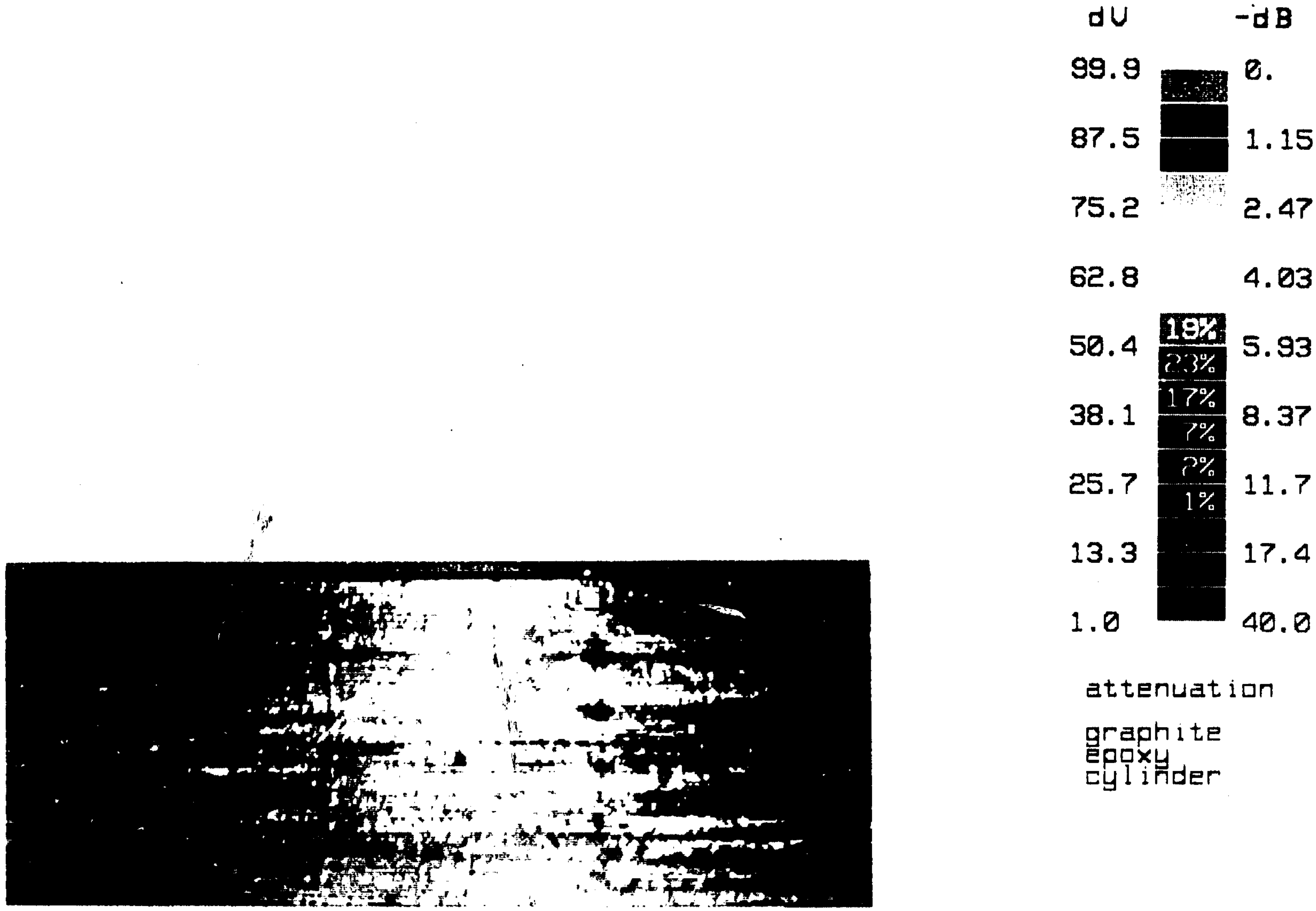


Figure 7. Attenuation C-scan of filament wound graphite epoxy cylinder.

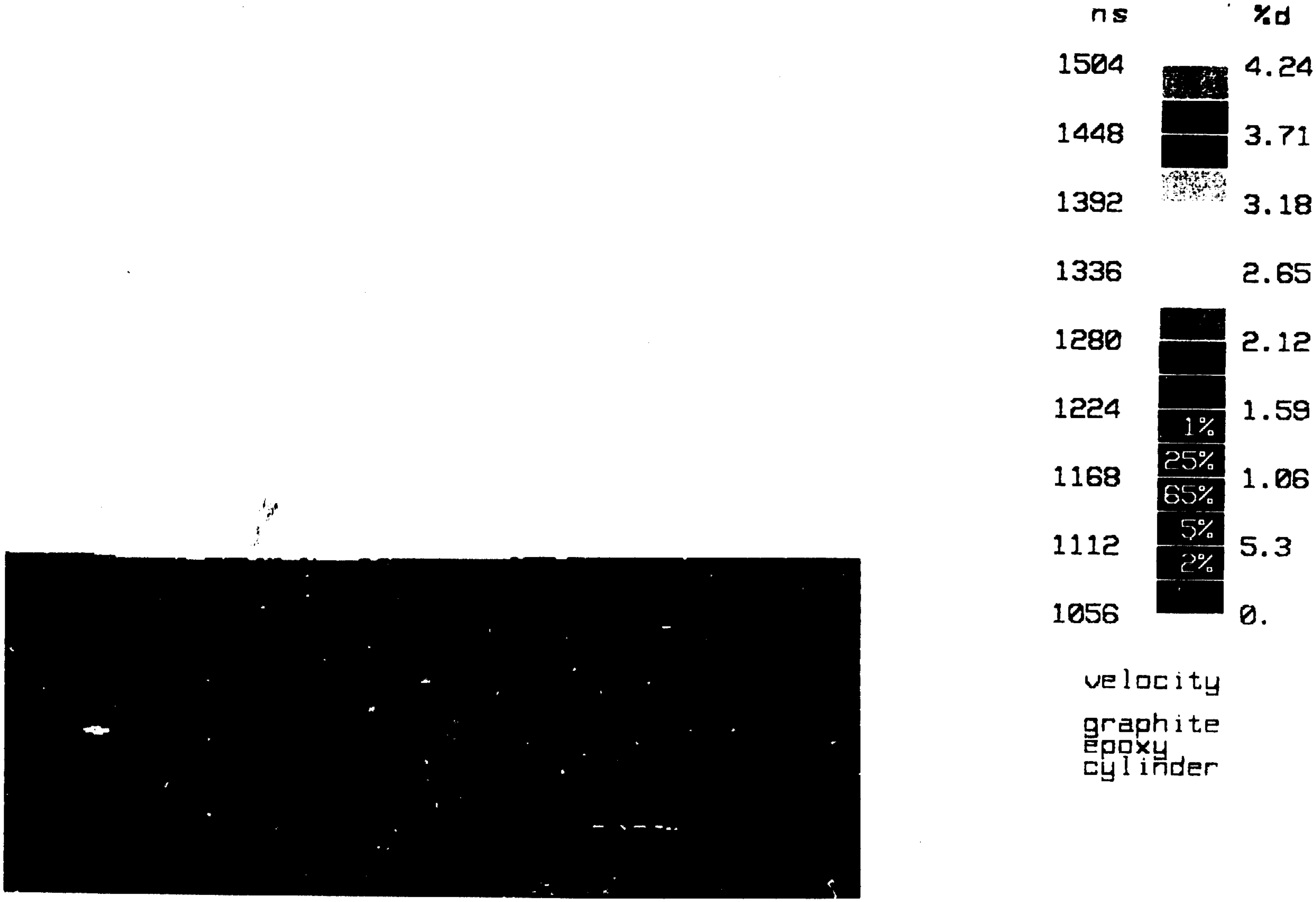


Figure 8. Velocity C-scan of filament wound graphite epoxy cylinder.

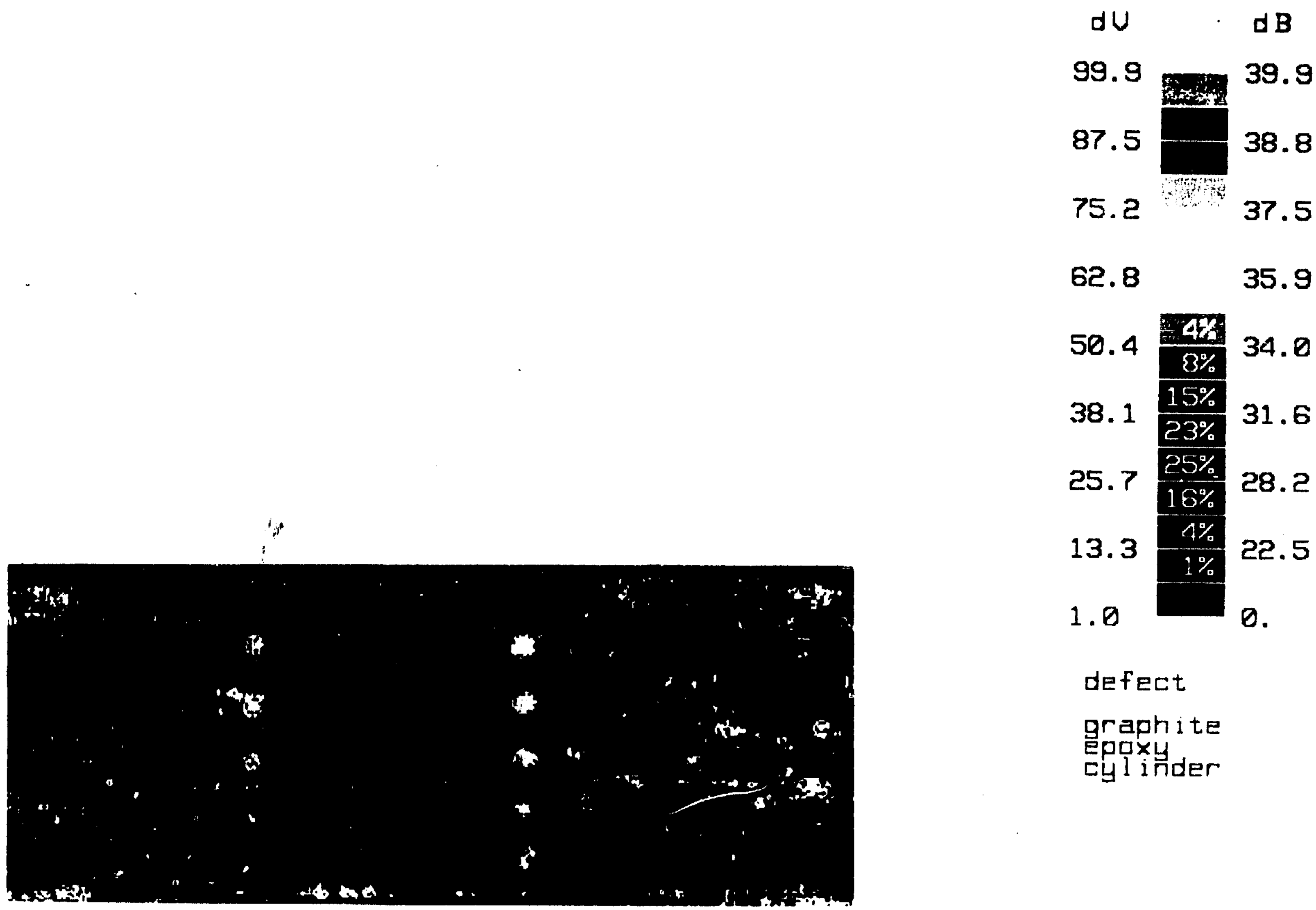


Figure 9. Defect C-scan of filament wound graphite epoxy cylinder.

APPENDIX A

FORMAL ULTRASONIC PROCEDURE FOR DEFECT SCANS OF FILAMENT WOUND GRAPHITE EPOXY CYLINDERS

PULSER/RECEIVER SETTINGS:

GATE:

Gate Status	ON
Sync	IF
Start Delay	0.450 μsec
Gate Length	0.550 μsec
Alarm Threshold	NORMAL
Level	33% F.S.
Alarm Polarity	POSITIVE
Audible Alarm	OFF
Noise Filter	OFF
Alarm Reset	AUTO

Receiver:

Gain	56.0 dB
Frequency	15 -> 25 MHz
Filter	OFF
Detector	FULL WAVE
Band Width	WIDE
Linear Reject	OFF
Back Echo Gate	OFF
Front End Atten	OFF

DAC:

Display	OFF

A-Scan Display:

Sweep Range	6.34 μsec
Display Channel	1 VIDEO
Sync Channel 1	DELAY
Sync Channel 2	IP
Sweep Delay Sync	IF CH 1
Sweep Delay Length	0.050 μsec

Ultrasonic Setup:

Units	μsec
Rep Rate Trigger	INTERNAL
Frequency	600 Hz
Material Velocity	2381 m/sec

Pulser:

Pulse Damping	50 ohms
Receiver Input	ECHO

COMPUTER SETTINGS:

Scan Direction	T
Index Direction	Z
Scan Length	5600
Scan Speed	15 rpm
Resolution	HIGH

TRANSDUCER:

Frequency	15 MHz
Diameter	0.25 inch
Focal Point	UNFOCUSED
Serial #	84023
Manufacturer	PANAMETRICS

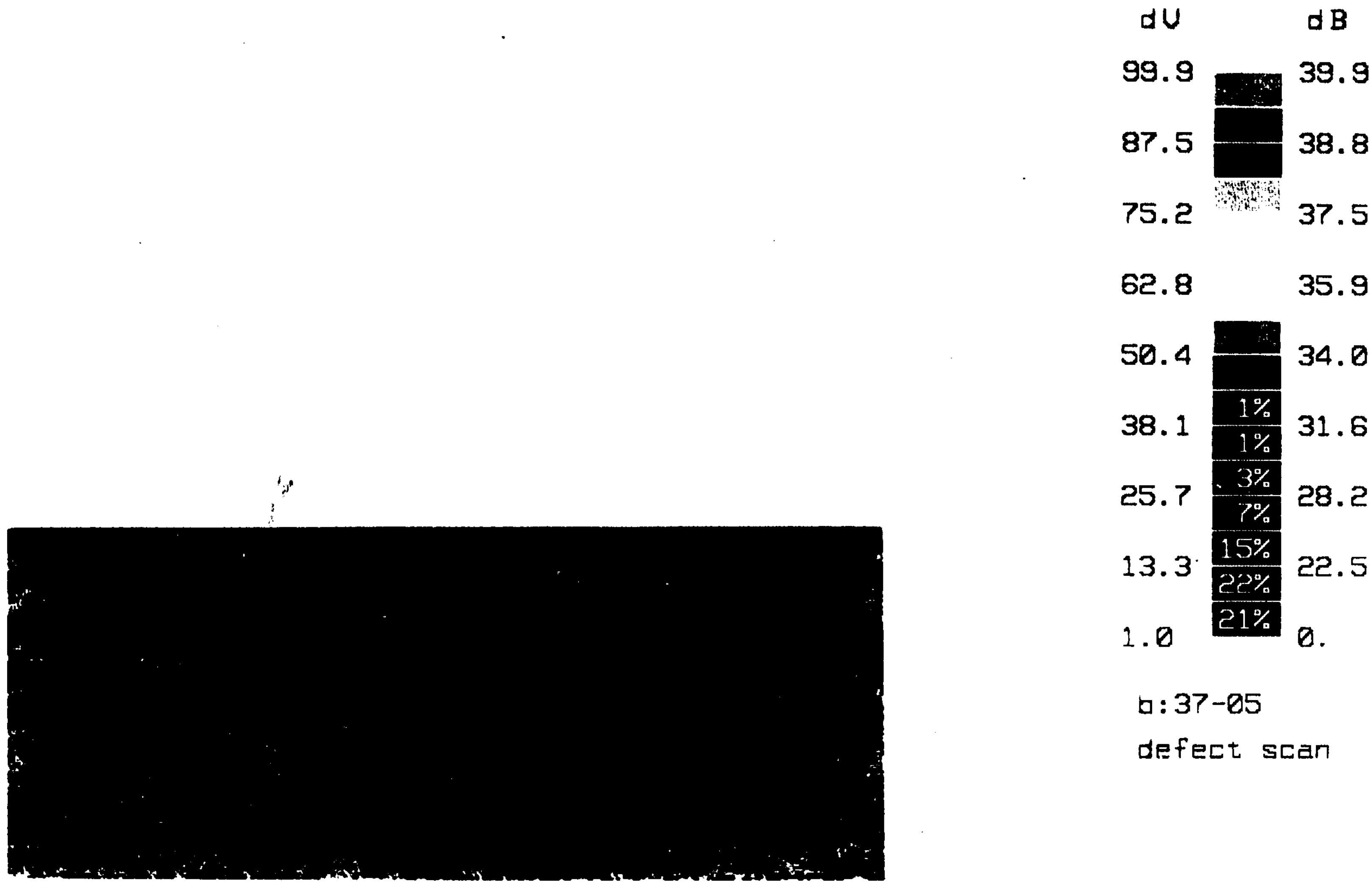
MISCELLANEOUS SETTINGS:

Testech MIS-100 Scanner:

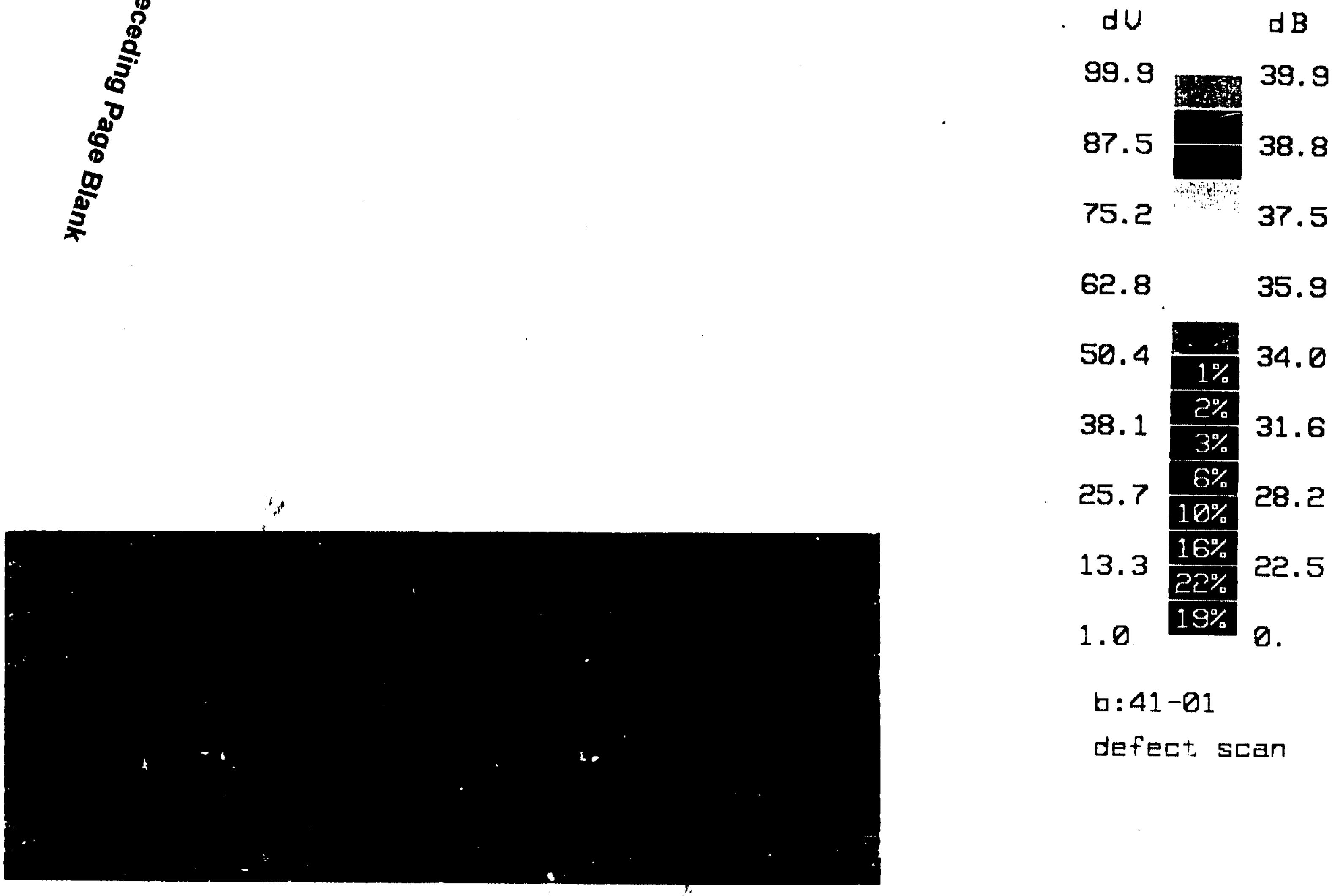
Z Coordinate	12.250

APPENDIX B

SELECTED SCANS



C-scan of cylinder showing no defects present.



C-scan of cylinder showing slight attenuation of sound.

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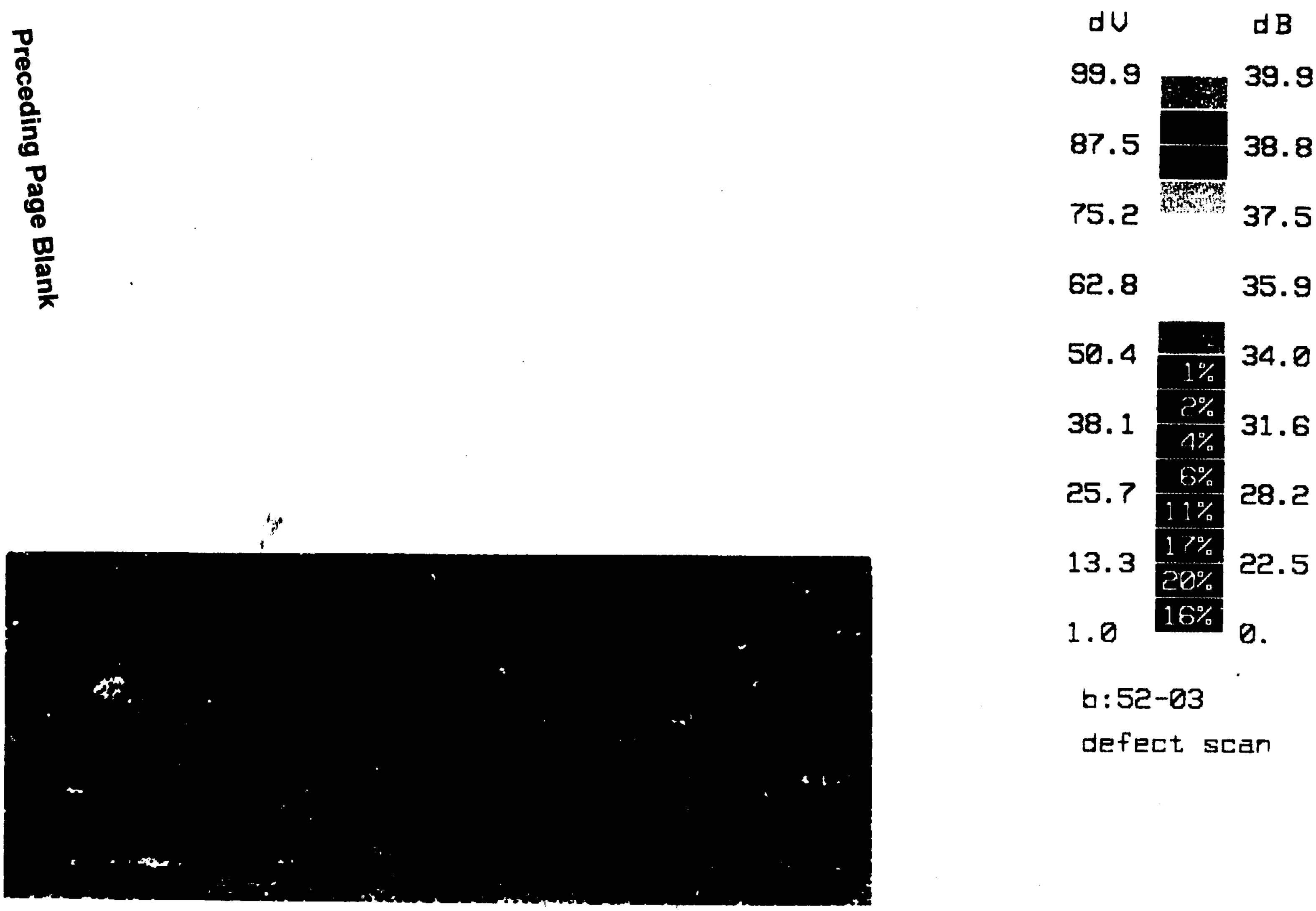
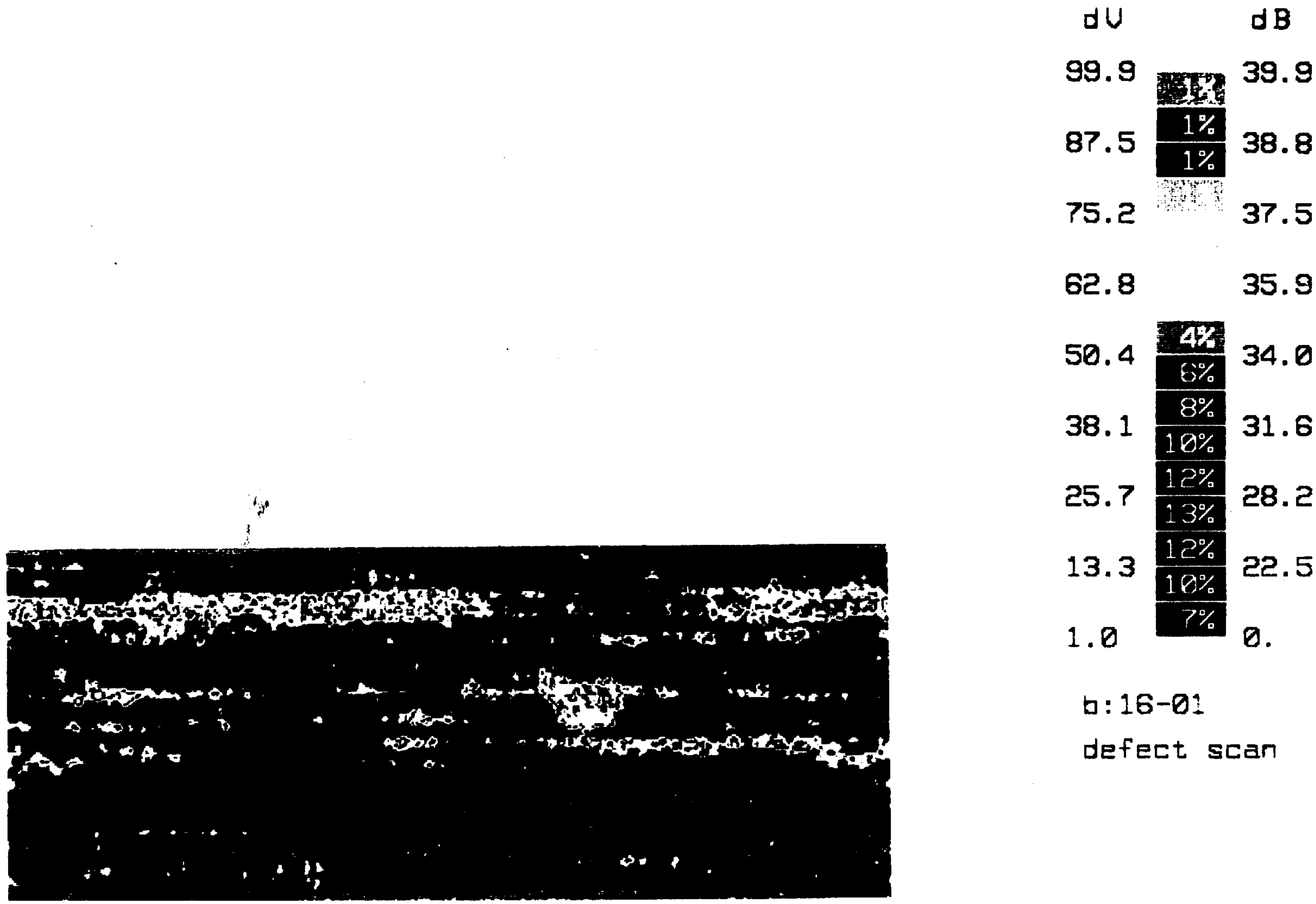


C-scan of cylinder showing small defect on left side (yellow/red area)



C-scan of cylinder showing major defect (pink area).

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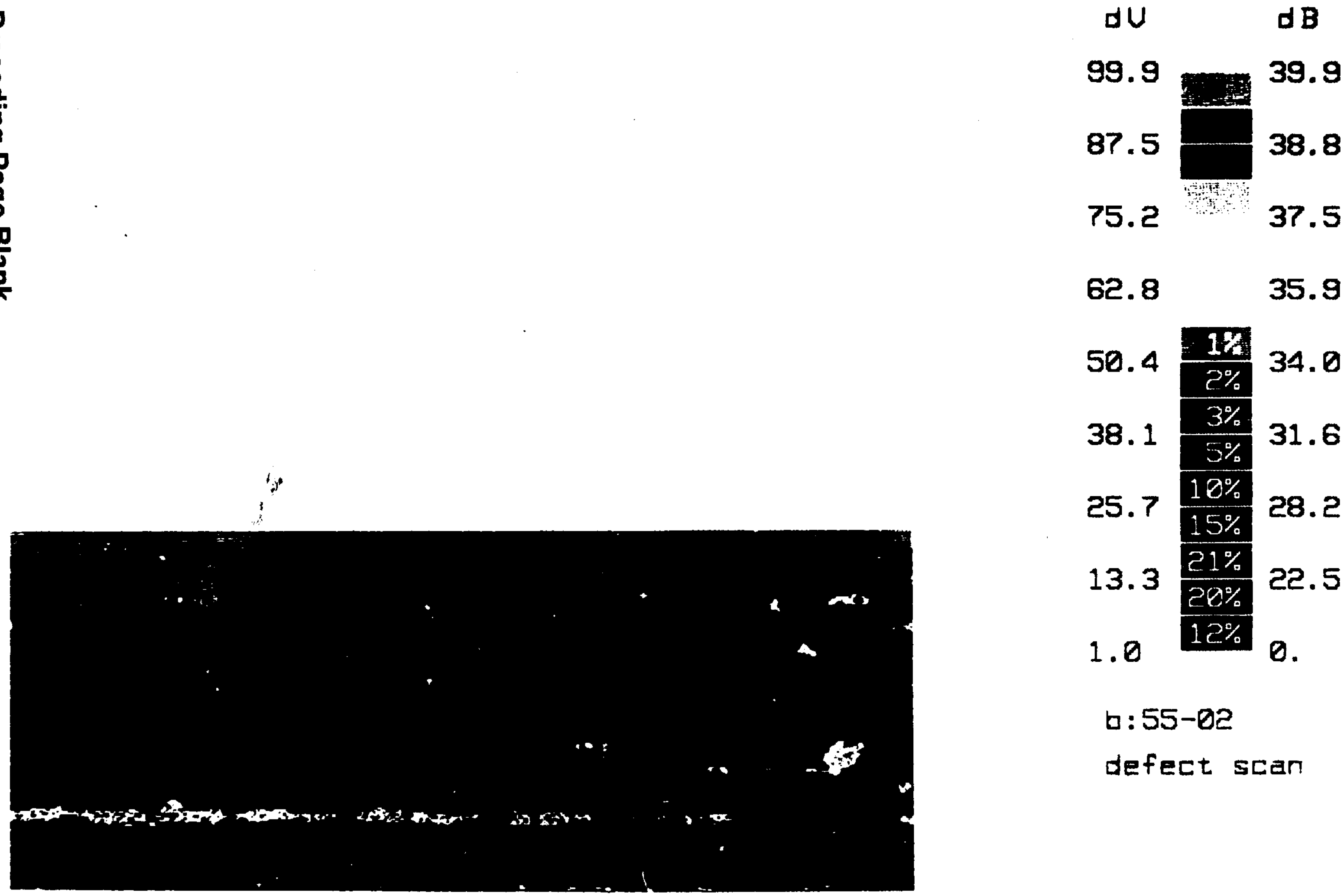

C-scan of cylinder showing longitudinal defect running through the length of the scan.

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ULTRASONIC INSPECTION OF FILAMENT WOUND GRAPHITE EPOXY CYLINDERS-
Lisa A. Tardiff and Bradley M. Taber, III

Technical Report MTL TR 92-61, September 1992, 30 pp-illus

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A nondestructive inspection procedure utilizing ultrasonic C-scan imaging was developed to test cylindrical filament wound graphite epoxy rocket motor cases. These cylinders are part of a joint U.S. Army, Navy, NASA, and Air force (JANNAF) research round robin to evaluate destructive testing techniques for this type of composite. The rocket motor cases are made from T650/42 graphite fibers (Amoco) in a Lincoln Resin Formulation (LRF) and have six layers (twelve plies). The ultrasonic method used to evaluate the rocket motor cases was immersion, pulse-echo defect C-scans. Difficulties and solutions of using this method to evaluate the rocket motor cases will be discussed. The received ultrasonic signals were evaluated for reflections from discontinuities within the material by means of an electronic gate set between the front and back surface reflections. The signals were then imaged in color on a computer according to the amplitude of the reflections. The resultant color C-scans were evaluated to separate the good from the bad. In some rocket motor cases there appeared to be large delaminations and inclusions. There were also some that showed few or no defect indications. Ultrasonic attenuation and time-of-flight (velocity) scans were performed to evaluate their quality. Contact time-of-flight measurements were also taken on a number of cylinders to verify immersion results. Comparisons will be made with transverse compression, transverse tension, and in-plane shear destructive test results. These comparisons will verify the usefulness of electronically gated ultrasonic immersion, pulse echo, defect C-scans on filament wound cylinders.

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